PETROGRAPHIC STUDY OF SELECTED BASALTS FROM MT. KILIMANJARO, TANZANIA

A Thesis

Presented in Partial Fulfillment of the
Requirements for the Degree
Bachelors of Science

by

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Abstract

Thin sections were made of rocks collected from Mt. Kilimanjaro, Mt. Meru, Ngorongoro crater, and Lake Manyara in northern Tanganyika. Descriptions of the sections showed the rocks to be critically undersaturated Alkali basalts composed primarily of plagioclase An_{27}-An_{60}, augite, and forsteritic olivine.

I thank Dr. Gunter Faure and Terri Mensing
for their time and patience.

Table of Contents

List of Figures

List of Tables

List of Graphs

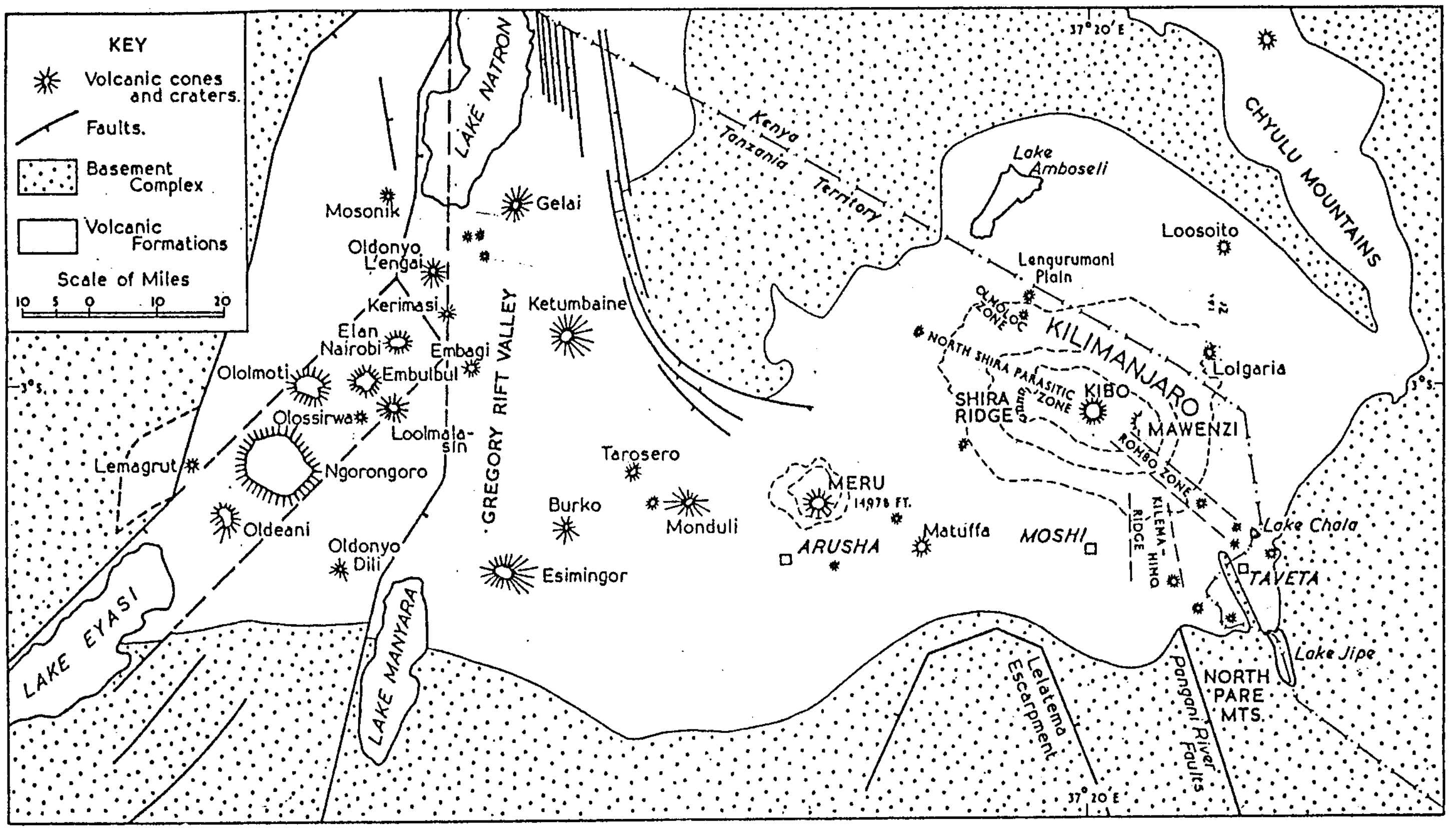


Figure 1.-The Geological Setting of the Kilimanjaro area. (After Downie and Wilkinson, 1972).

Introduction

Mt. Kilimanjaro, the highest mountain in Africa and one of the highest volcanoes in the world, is located at 3 degrees S and 37 degrees 20′ E in northern Tanganyika near the border of Kenya (Sampson, 1981) (See Figure 1). The base of the mountain covers an area approximately 60 miles long and 40 miles wide, trending ESE-WNW (Downie and Wilkinson, 1972). The mountain, in the form of a shield, rises to an elevation between 12,000 and 14,000 feet (Wilcockson, 1956). Three volcanic centers rise from this platform. Shira Ridge in the west reaches 13,140 feet, Kibo in the center rises to 19,340 feet, and Mawenzi in the east attains 16,896 feet. Numerous parasitic cones occur in zones on Kilimanjaro (Wilcockson, 1956). The mountain rests on a Precambrian basement exposed in Middle and Late Tertiary times (Downie and Wilkinson, 1972) (See Figure 2).

Kilimanjaro is bordered on the north by Amboseli Plains at an elevation of approximately 4000 feet, on the south by the Serengeti Plains of Kenya ranging from 2500 to 3500 feet, and on the west by hummocky terrain rising toward Mt. Meru at an elevation of 3500 to 4500 feet (Downie and Wilkinson, 1972) (See Figure 3).

The mountain, a basalt-trachyte-phonolite volcano, is situated near the intersection of the NNW-SSE Pangani Valley

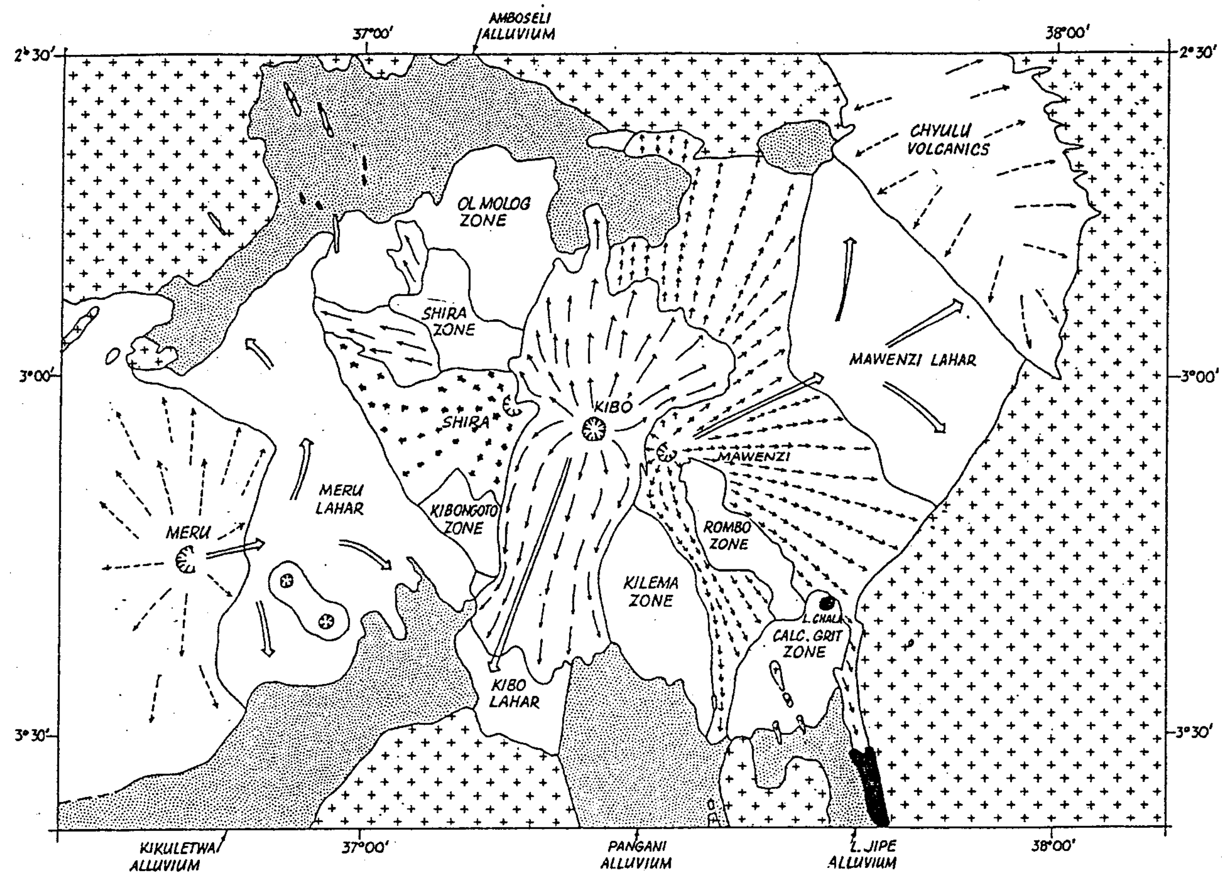


Figure 2.-The major geological features on Mt. Kilimanjaro. Solid arrows indicate the direction of lava flows, open arrows that of lahars. Dots indicate sedimentary rock, crosses represent the Precambrian basement. Lakes are shown black. (After Downie and Wilkinson, 1972).

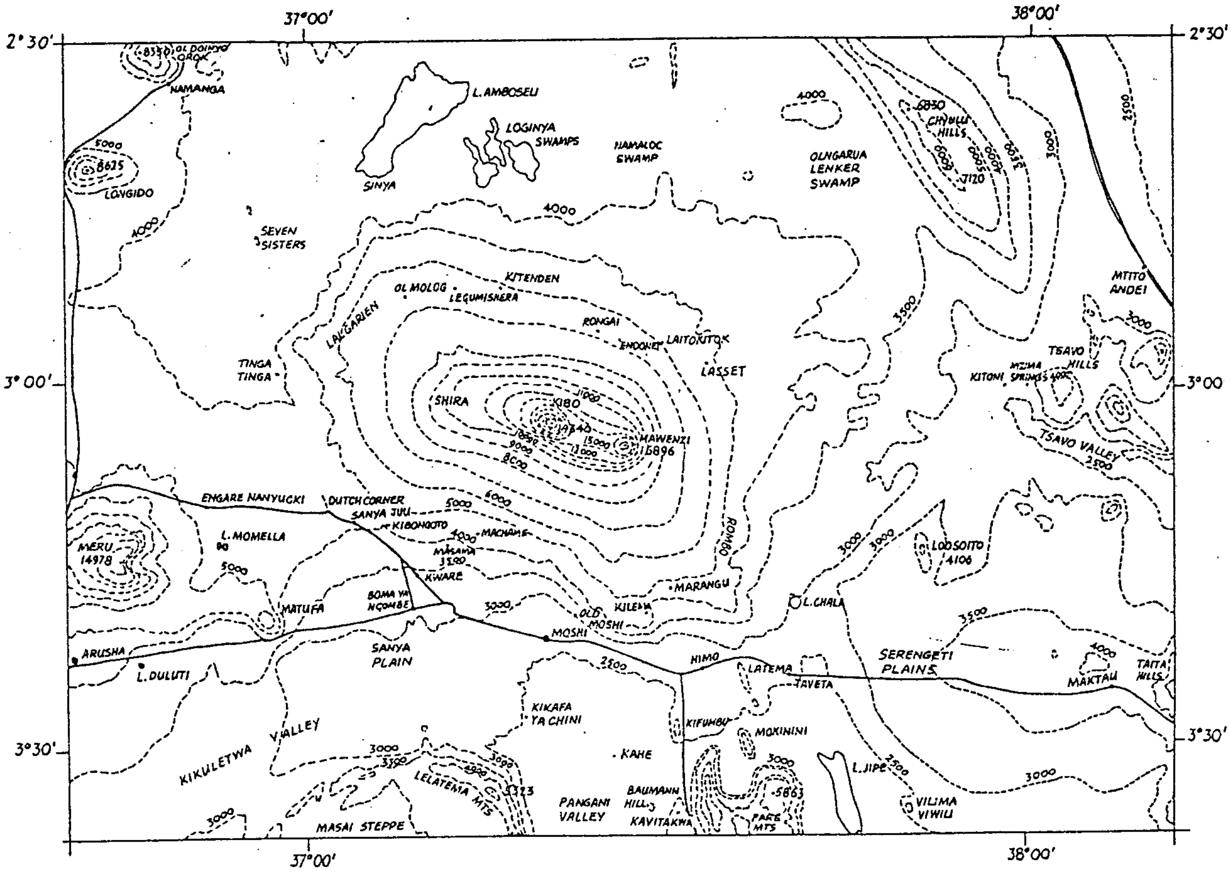


Figure 3.-The main topographic features of Kilimanjaro and the surrounding area. (After Downie and Wilkinson, 1972).

Fault, and an ENE-WSW line of volcanoes including Mt. Meru, Monduli, and Esiminger (Williams, 1970) (See Figure 1). Volcanic activity began during major faulting in the area in Middle and Late Tertiary times. Most of the volcanic activity on Kilimanjaro occurred during the Pleistocene and is possibly still going on (Downie and Wilkinson, 1972) (See Table A1).

Samples were taken primarily from Mt. Kilimanjaro, but also from several nearby locations including Mt. Meru, Lake Manyara, and the Ngorongoro caldera. Mt. Meru, a nephelinite-trachyte volcano active from the Pliocene to Recent, is located approximately 50 km southeast of Kilimanjaro near Arusha, and stands 14,979 feet. Lake Manyara is located around 180 km to the southwest of Kilimanjaro, while Ngorongoro Crater is found in northern Tanganyika approximately 130 km west of Kilimanjaro (Geological Survey of Tanganyika) (See Figure 1).

Kibo

Kibo is the highest peak on the mountain and was the last active volcanic center. At its base, lavas of Mt. Kibo have spilled over those of both Mawenzi and Shira (Downie and Wilkinson, 1972). It rises from the saddle at 14,000 feet to 19,340 feet at its ice-covered summit. The circumference of the cone at saddle level is more than 15 miles (Wilcockson,1956). The summit has subsided to form a caldera 1.5 miles in diameter with inner walls up to 600

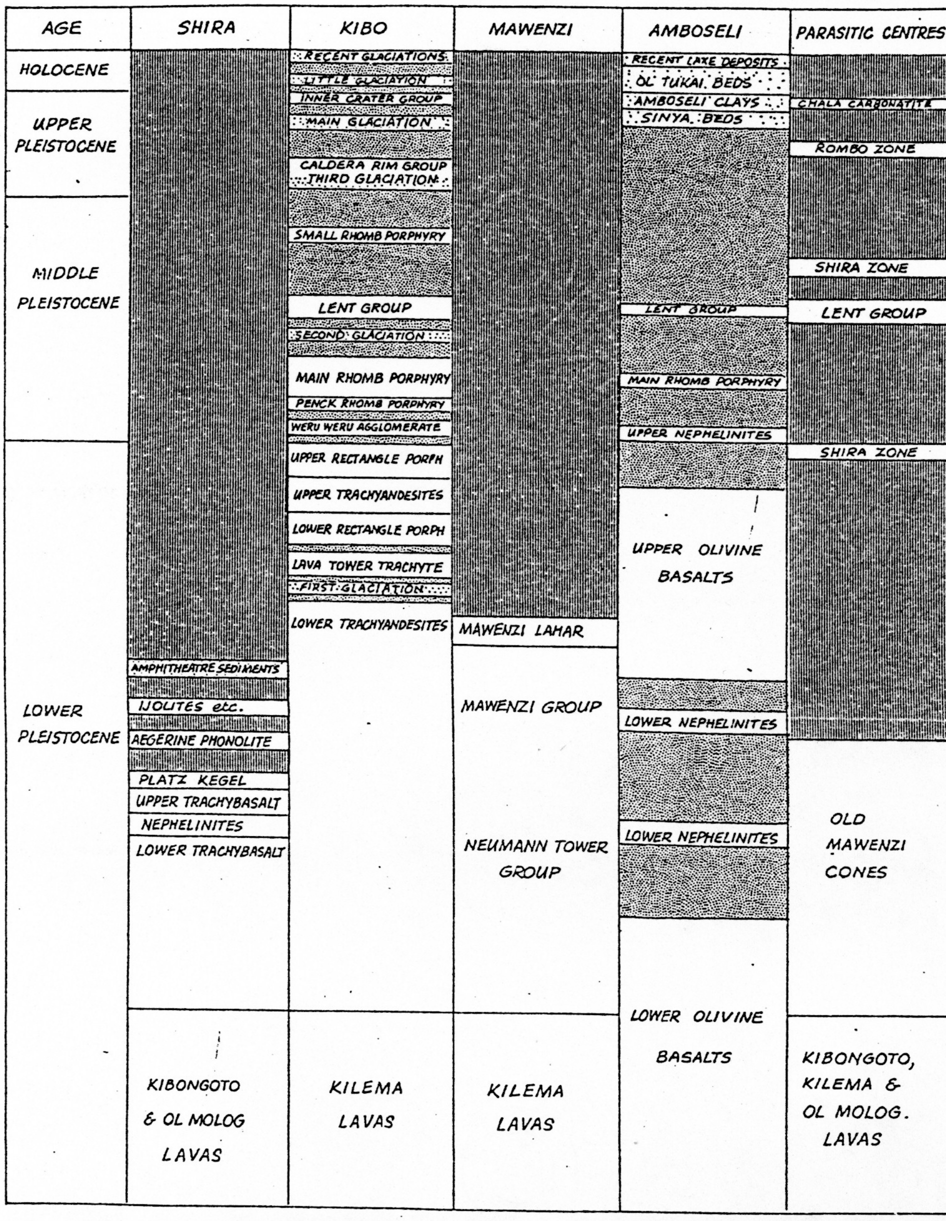


Table A1.-Correlation of lavas. (After Downie and Wilkinson, 1972).

feet high on the south side. This caldera contains an Inner Cone rising to over 19,000 feet. An inner crater 900 yards in diameter has punctured the inner cone and contains a third cone, known as the Ash Cone. This structure contains a central crater, named the Ash Pit, 370 yards in diameter and 425 feet deep (Wilcockson, 1956) (See Figure 4).

There is a succession of seven lava types on Kibo which dip gently in a radial pattern away from the summit (See Table A2). These lavas are more diverse and show a more complete differentiation than those at Mawenzi or Shira. Early lavas, covered by later ones, are relatively unknown except where exposed near the Great West Notch and at Kibo Barranco (Wilcockson, 1956).

Trachyandesite is the earliest lava at Kibo and strongly resembles the trachybasalt at Mawenzi and Shira. It has been divided into two groups. Both groups are characterized by tabular feldspar phenocrysts of labradorite (Downie and Wilkinson, 1972). The Lower Trachyandesite group, which erupted when the main vent stood approximately 17,000 feet, is not widespread. Only two exposures are known, one along Bastion Stream, and the other along the Upper Umbwe (Downie and Wilkinson, 1972). The base of the Lower Trachyandesite group is not exposed and the entire lower portion of the mountain might be composed of this or trachybasalt (Wilcockson,1956) (See Figure 5). A single basaltic dyke has been found in this group. It is older than the overlying Lava Tower Trachytes (Downie and

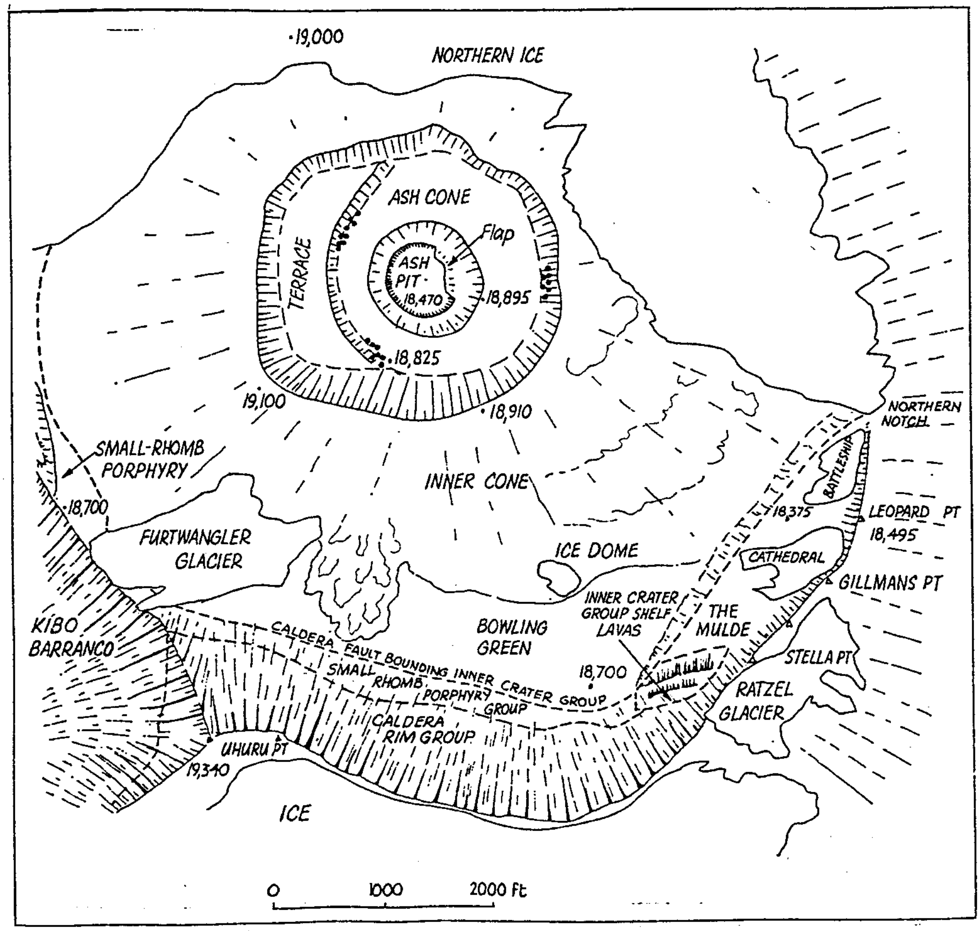


Figure 4.-The main topographic features of the caldera area of Kibo. (After Downie and Wilkinson, 1972).

Inner Crater group)
erosion)____________Upper Pleistocene
Caldera Rim group)
erosion)

Small-Rhomb Porphyry group)
erosion)
Lent Group)____Middle Pleistocene
erosion)
Rhomb-Porphyry group)
erosion)

Upper Rectangle Porphyry group)
Upper Trachyandesite group)
Lower Rectangle Porphyry group)
erosion)-Late Pleistocene
Lava Tower Trachyte group)
erosion)
Lower Trachyandesite group)

Table A2.-Succession of lavas on Kibo. (From Downie and Wilkinson, 1972).

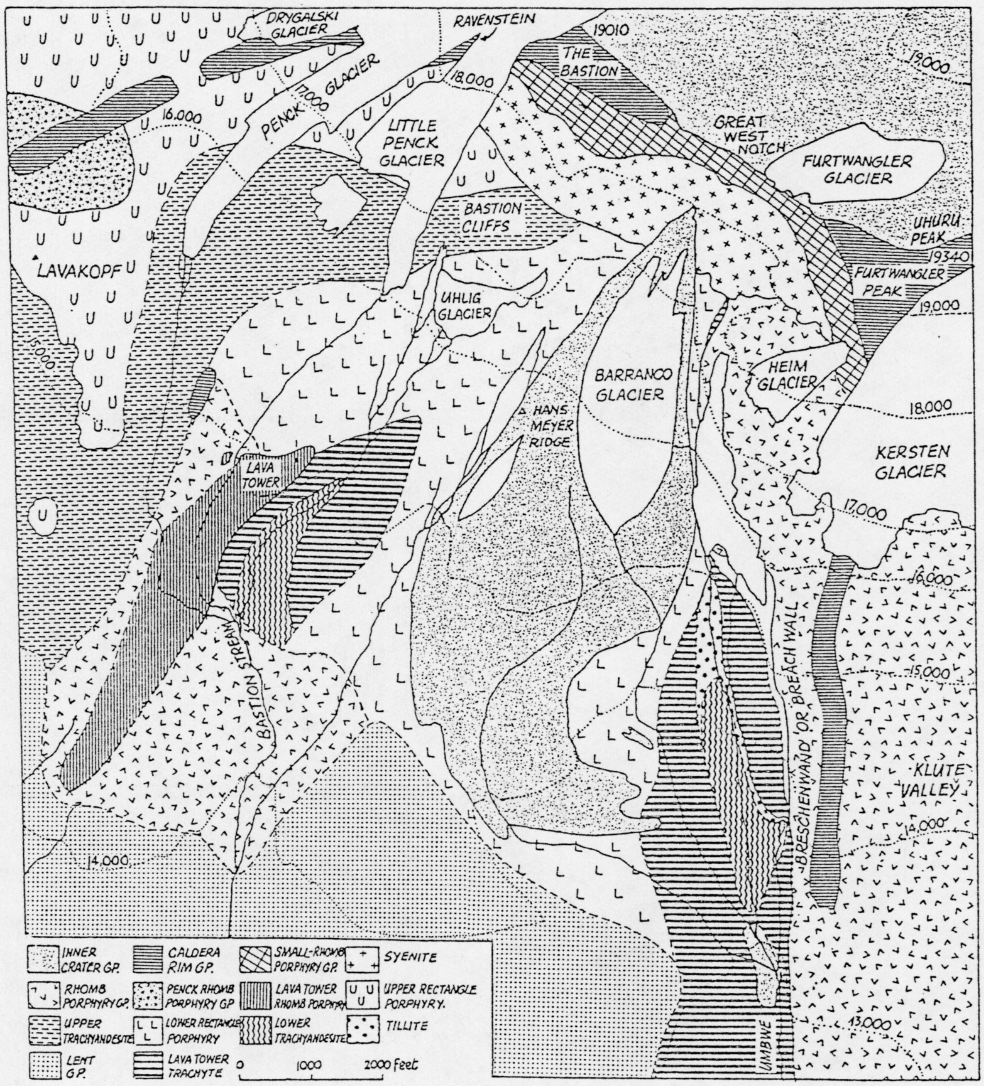


Figure 5.-A geological map of the Barranco area of Kibo. (After Downie and Wilkinson, 1972).

Wilkinson, 1972).

The Lava Tower group consists of aegerine-rich trachytes. They have a greenish color and chloritic sheen (Downie and Wilkinson, 1972). This group, which also erupted from the main vent, contains xenoliths of basalt, trachybasalt, trachyandesite, and rectangle-porphyry .

The Lower Rectangle Porphyry, restricted in outcrop to the Kibo Barranco area, follows the Lava Tower group and is characterized by prismatic phenocrysts of oligoclase and andesine (Downie and Wilkinson, 1972). The rocks are trachyandesites.

The Upper Trachyandesite is the first widespread group on Kibo. These lavas were erupted when the main vent stood at a height of approximately 19,000 feet (Downie and Wilkinson, 1972).

The Upper Rectangle Porphyry group occurs predominantly on the west side of Kibo where it is widely distributed, stretching to the Shira Plateau (Wilcockson, 1956). The rocks are trachytes and trachyandesites containing rhombic anorthoclase and oligoclase phenocrysts up to 20 mm in size. This group also contains the Wesu Wesu Agglomerate, the largest pyroclastic deposit on Kibo (Downie and Wilkinson, 1972).

The Normal Rhomb Porphyry group contains rhombs of anorthoclase with an edge-length of up to 40 mm. Some orthoclase phenocrysts have been found. These lavas, composed of trachytes, extend over a greater area than any other on

Kibo (Downie and Wilkinson, 1972).

The Lent Group, consisting of trachytes, phonolitic-trachtes, and phonolites erupted from four main centers on the flanks of Kibo. They cover large areas of the north and south sides of the cone. The flows invariably contain obsidian (Downie and Wilkinson, 1972).

The small Rhomb Porphyry group, containing rhombs of anorthoclase up to 1.27 cm, are found in the Kibo-Barranco and extensively spilled over the southeast side of Kibo (Wilcockson, 1956). The rocks, which frequently contain nepheline phenocrysts, have been classified as nepheline phonolites. An analcime syenite body associated with the Small Rhomb Porphyry forms cliffs 300 to 400 feet high across the Kibo Barranco (Downie and Wilkinson, 1972).

The Caldera Rim Group, composed of phonolites, contains large rhombic anorthoclase phenocrysts along with smaller phenocrysts of nepheline (Downie and Wilkinson, 1972). Thick sequences of this lava have filled the eroded caldera of the Small Rhomb Porphyry, and have spilled down the flanks of Kibo (Wilcockson, 1956).

The youngest lava is the Inner Crater group consisting of nephelinites or nepheline phonolites with conspicuous glassy nepheline and pyroxene phenocrysts in a glassy or micro-crystalline matrix (Wilcockson, 1956). Some contain small phenocrysts of anorthoclase or sanidine (Downie and Wilkinson, 1972). This series probably extruded from the ring fracture of the caldron subsidence of the Caldera Rim group, covered the caldera floor, and spilled over the rim at the Great West Notch, as well as over the northeast caldera rim of Kibo (Wilcockson, 1956).

Mawenzi

Mawenzi, the eastern volcanic center and the second to become inactive, rises from a saddle elevation of 14,000 feet to 16,896 feet at its summit (Sampson, 1981). The cone is highlyeroded, a horse-shoe shaped remnant of a stratiform volcano. Practically the entire east side of the volcano is missing due to erosion. While the western ridge, containing the highest peaks, is believed to closely mark the site of the original crater, it is not known to actually be the crater wall.

Below 11,000 feet Mawenzi is composed of thin broad lava flows containing no pyroclastic material. At 11,000 feet pyroclastic material appears and gradually increases in abundance until it composes 30-40% of the rock at the vent.

Two main vents occur on Mawenzi, 1.5 miles apart. The eastern vent is found near Neumann Tower, while the other, known as the Main Mawenzi Centre, is situated in the recess of the Great Barranco beneath Pinnacle Col (See Figures 6 and 7). Four other less important vents occur nearby (Downie and Wilkinson, 1972).

The Main Mawenzi Centre is surrounded on three sides by cliffs rising 1000-2000 feet and is accessible only in the east where the Great Barranco has removed the crater wall.

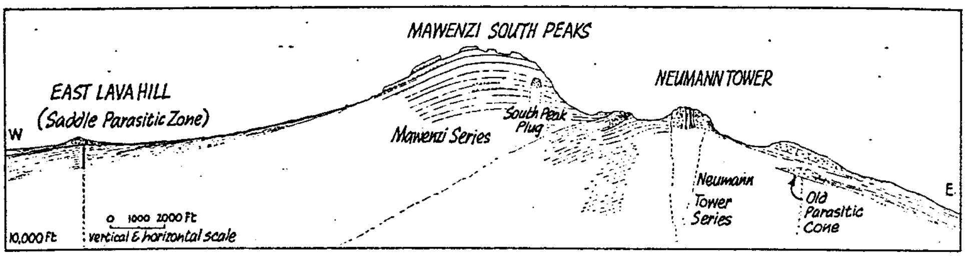


Figure 6.-East-west cross-section of Mawenzi, showing relationships between the main centers and the internal structureof the Neumann Tower vent. (After Downie and Wilkinson, 1972).

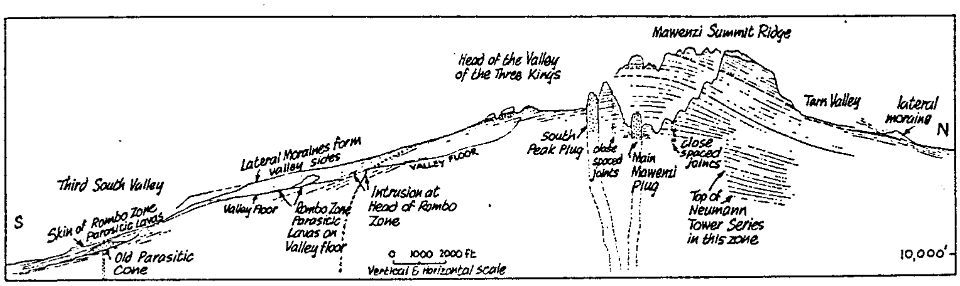


Figure 7.-North-south cross-section of Mawenzi, showing relationships between the main lava groups and the internal structure of the Main Mawenzi vent. (After Downie and Wilkinson, 1972).

The circular crater, with a diameter of about 0.75 miles, contains agglomerate consisting of feldsparphyric trachybasalt. It is surrounded at its margins by vertical intrusions of syenogabbro. A large plug of syenogabbro now surrounded by cliffs 100-350 feet high has been exposed in the eastern portion of the center and probably marks the site of the last vent of the final crater of Mawenzi (Downie and Wilkinson, 1972).

Neumann Tower rises 14,510 feet from the southeast corner of the Great Barranco. It lies in the center of a major focus of eruption. Agglomerate containing basalts and trachybasalts occur in the 1000 to 1400 feet diameter center. Neumann Tower was once the major site of volcanic activity in the area but gradually was overtaken by the Main Mawenzi Center, became inactive, and was almost obliterated before Mawenzi Centre also became inactive.

The South Neumann Tower Centre, 800 feet south of Neumann Tower, contains a crater 500 feet in diameter. Basalt and trachybasalt bearing agglomerate is found in the crater. A vertical plug 100 x 200 feet in cross-section of medium grained grey potash syenite is found in the middle of the vent (Downie and Wilkinson, 1972).

The South Peak Plug, a vertical cylinder 500 x 300 feet in cross-section composed of syeno-gabbro, is located near the outer edge of the Main Mawenzi crater (Downie and Wilkinson, 1972).

West Neumann Tower, a horizontal cylindrical pipe of unknown composition, is found 1500 feet west of Neumann Tower.

The rocks on Mawenzi are divided into two groups, the Neumann Tower Group and the Mawenzi Group. Also present is the Rombo Zone Parasitic Group. These lavas occur in alternating sheets throughout the section with the oldest lavas belonging to the Neumann Group (Downie and Wilkinson, 1972). Almost the entire cone is composed of Neumann Tower lava which consists predominantly of basic lavas, basalts, and ankaramites, intercalated with more acid felsparphyric basalts and trachybasalts, and also trachyandesites. The Mawenzi Group does not become important until late in the life of the volcanic center and forms only a relatively thin veneer on top of the mountain.

Over 1000 narrow dykes, extensive in length and depth, are found on the cone. These dykes are usually 2-3 feet wide with many less than one foot and a few more than six feet thick. Most run ESE-WNW, but many are radial (Wilcockson, 1956).

The dykes are grouped into four main categories: the Main Swarm, symmetrically arranged on both sides of the axis connecting the two main vents; the Concentric Sheets, which form concentric rings around Mawenzi; the Main Mawenzi Radial Dykes and the Neumann Tower Radial Dykes, both of which extend outward from their respective centers in a radial pattern (Downie and Wilkinson, 1972).

Shira

Shira, the oldest of the three centers, is found west of Mawenzi (Sampson, 1981). It is highly eroded, forming the Shira Plateau 12,000 feet above sea level, and is now represented only by the Shira Ridge which is the western crater wall (Wilcockson, 1956) (See Figure 8). Although the cone may have stood as high as 18,000 feet at one time, it now rises to only slightly above 13,000 feet along Shira Ridge. The cone is mostly composed of basic and undersaturated lavas, associated flow breccia, and considerable amounts of agglomerate and tuff. What was once thought to be a subsidence caldera two miles in diameter at the base of Shira Ridge is now considered an eroded crater (Downie and (Wilkinson, 1972). No ring fractures have been found and the rock present, formally called the Caldera Floor Series is now included in the Lower Trachybasalt group.

Two small cones are found in the crater. One, composed of glassy green aegerine nephelinite exhibiting strong flow banding rests on the northwest slope of the crater, below Shira Ridge. The other, a solitary horse-shoe shaped hill one mile across and opening to the north rises 800 feet from the crater floor. This ridge, known as Platzkegel, is composed of doleritic agglomerate, injected by dolerite, analcime, syenite, and essexite, with a tuffaceous matrix (Downie and Wilkinson, 1972).

The last phase of activity included the emplacement of thin dykes in a radial swarm. Approximately 150 dykes, one

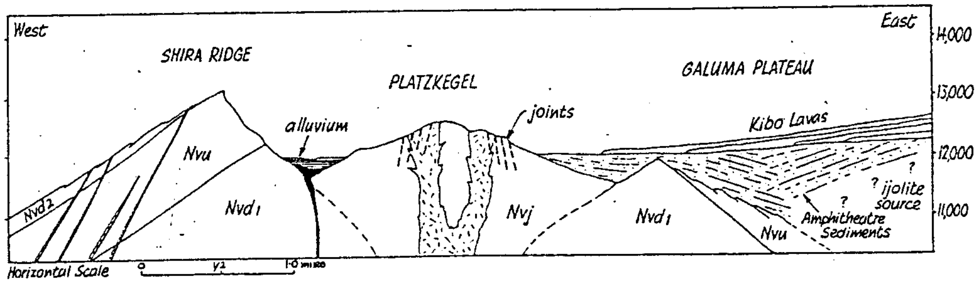


Figure 8.-East-west cross-section across Shira showing the relationships between the main formations. Nvd_1-Upper Trachybasaltic group; Nvu-Ultramafite and Melanephelinite group; Nvd_2-Lower Trachybasaltic group; triangles indicate the Platzkegel agglomerate; black indicates the aegerine phonolite and the broken ornament is the essexitic intrusion. (After Downie and Wilkinson, 1972).

to two feet thick, are found along the Shira Ridge. These dykes are dominantly trachyandesites and trachybasalts. Also at that time, several sheets were intruded into the flanks dipping outward at about 45 degrees. They are composed of rocks similar to trachybasalts and metatrachybasaltic lava (Downie and Wilkinson, 1972).

Erosion, along with lava flows and fluvioglacial deposits from Kibo have destroyed or obscured much of Shira. According to Wilcockson (1956), the rocks at Shira have been grouped into three series; the Caldera Rim Series, the oldest; the Caldera Floor Series; and the Platzkegel Series, the youngest. However, Downie and Wilkinson (1972) consider the Caldera Floor Series to be part of the Lower Trachybasalt Group and make no mention of the other two series.

Along Shira Ridge, where the crater wall rises steeply 1000 feet above the floor, the succession of lavas includes the Lower Shira Trachybasaltic Group, the overlying Shira Ultramafite and Melanephelinite Group, and the topmost Upper Shira Trachybasalt Group (Downie and Wilkinson, 1972). The Upper and Lower Trachybasalts, containing numerous platy plagioclase feldspars, strongly resemble the trachybasalts of Mawenzi (Wilcockson, 1956). The Shira Ultramafite and Melanephelinite Group, 400 feet thick, contains ultrabasic lavas bearing olivine, augite phenocrysts, and some nepheline phenocrysts up to one inch across.

Parasitic Cones

Numerous parasitic cones are usually found in well-defined zones, suggesting fracture belts. Zones include the Upper and Lower Rombo Zone to the southeast of Mawenzi, the Saddle Zone between Kibo and Mawenzi, and the North Shira Zone northwest of Kibo. Other zones, located in the forests and surrounding plains include the Lower Rombo Zone, Himo-Kilema Ridge, Lolgaria-Loosoito, North Shira, and Ol Morouk (See Figure 9).

All of the parasitic cones are small, generally not rising more than 350 feet above their surroundings. They are often well preserved with a distinct crater, but on the Saddle they have been eroded by glacial action leaving crag and tail features (Downie and Wilkinson, 1972).

Lavas extruded from the parasitic cones have concealed much of the flanks of the volcano, particularly to the southwest where the lava obscures much of the south side of the Saddle and the southeast side of Mawenzi. Lava reaches to Lake Chala and Taveta on the plain. In the northwest the lava reaches the Lengurumani Plain.

The cones are composed of various rock types. Olivine Basalt and Ultrabasic rocks bearing olivine and augite phenocrysts occur commonly in the cones. Most Saddle cones consist of cinder capped by basalt extruded after collapse of the crater. Cones in the Upper Rhomb Zone consist mainly of lava with subsidiary pyroclastic except in later stages, while the North Shira, Lower Rhombo, and Himo-Kilema Ridge

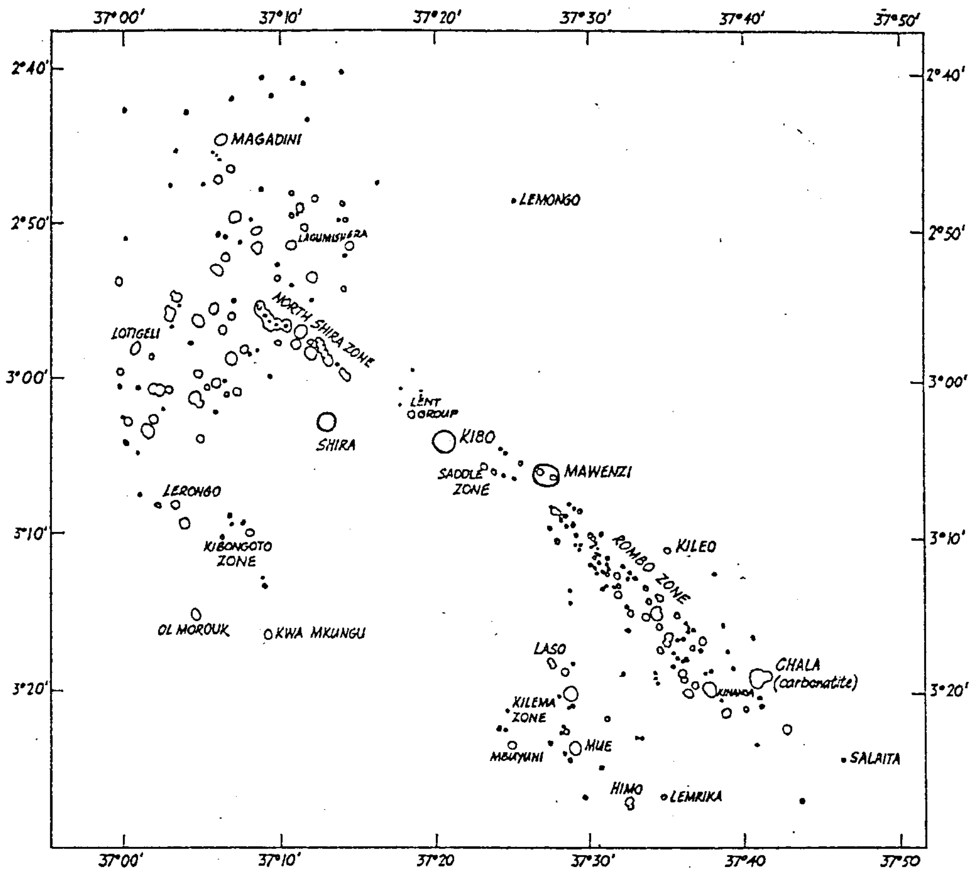


Figure 9-Map of the eruptive centers on Kilimanjaro showing Shira, Mawenzi, Kibo, and the many parasitic zones. (After Downie and Wilkinson, 1972).

cones have been built up of lava and pyroclastics (Downie and Wilkinson, 1972).

Age

Most of the rocks on the mountain were extruded during the Pleistocene epoch (See Table 1). However, volcanic ac- began in association with faulting in Middle Tertiary times. Trachybasalts, the oldest rocks exposed on the mountain, are probably contemporaneous for all three volcanic centers. These rocks may be of Pleistocene age or older. Absence of glacial deposits suggests a pre-Pleistocene age. All post-trachybasalt lavas and parasitic cones probably formed during the Pleistocene. The Rhomb Porphyry and Rectangle Porphyry of Kibo rests on the eroded cone and caldera of Shira, so that almost all of Kibo activity took place after Shira became inactive (Wilcockson, 1956). Most of Kibo's activity also took place later than that of Mawenzi, as shown by the presence of Kibo's Rhomb Porphery resting on various levels of Mawenzi trachybasalts and basalts. Only the Inner Crater Series on Kibo may be as young as the Holo-cene.

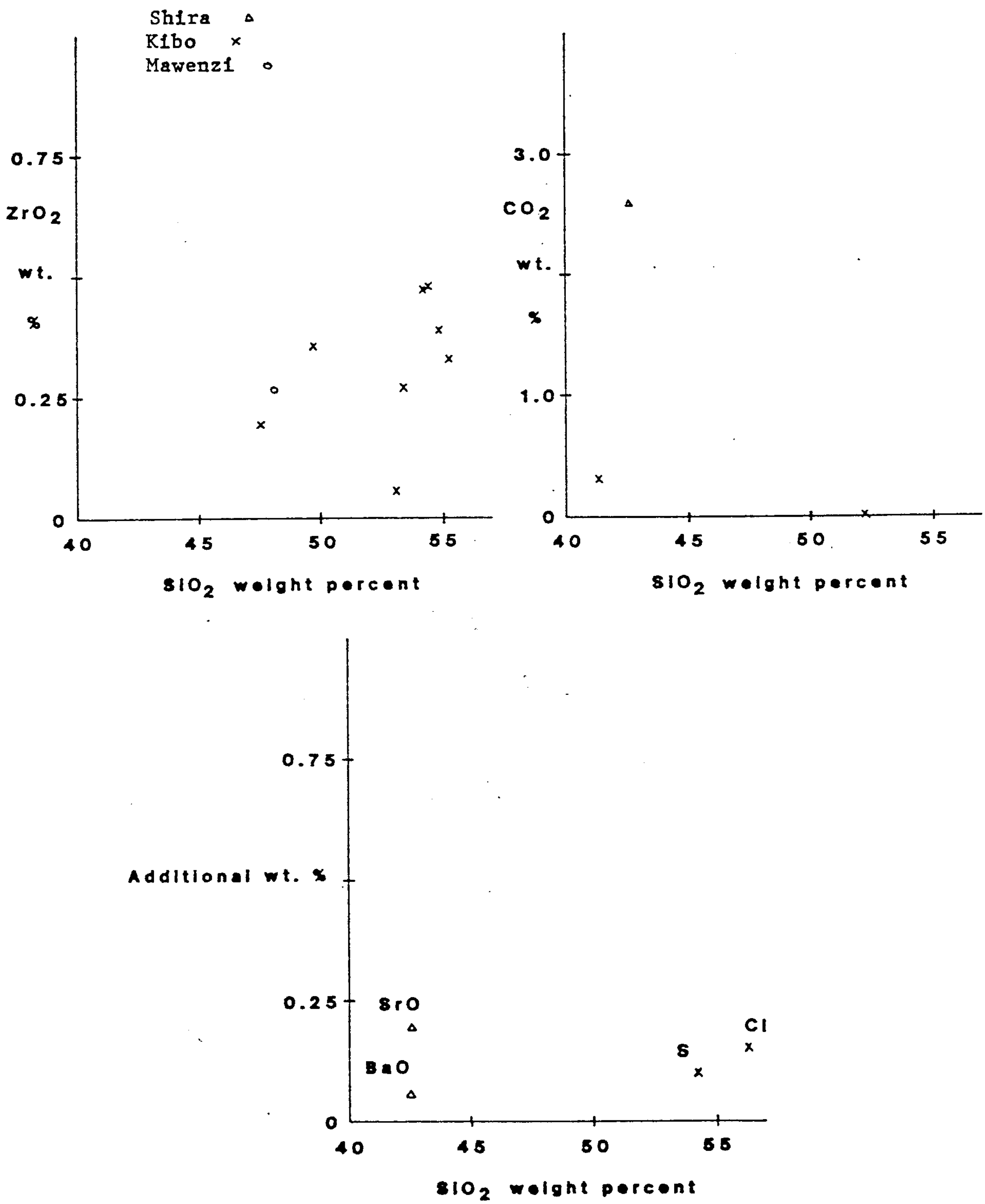
Chemical Composition of the Flows

Chemical analyses of the rock samples collected at the three main volcanic centers of Kilimanjaro indicate that the lavas represent increasing degrees of differentiation of a single magma body.

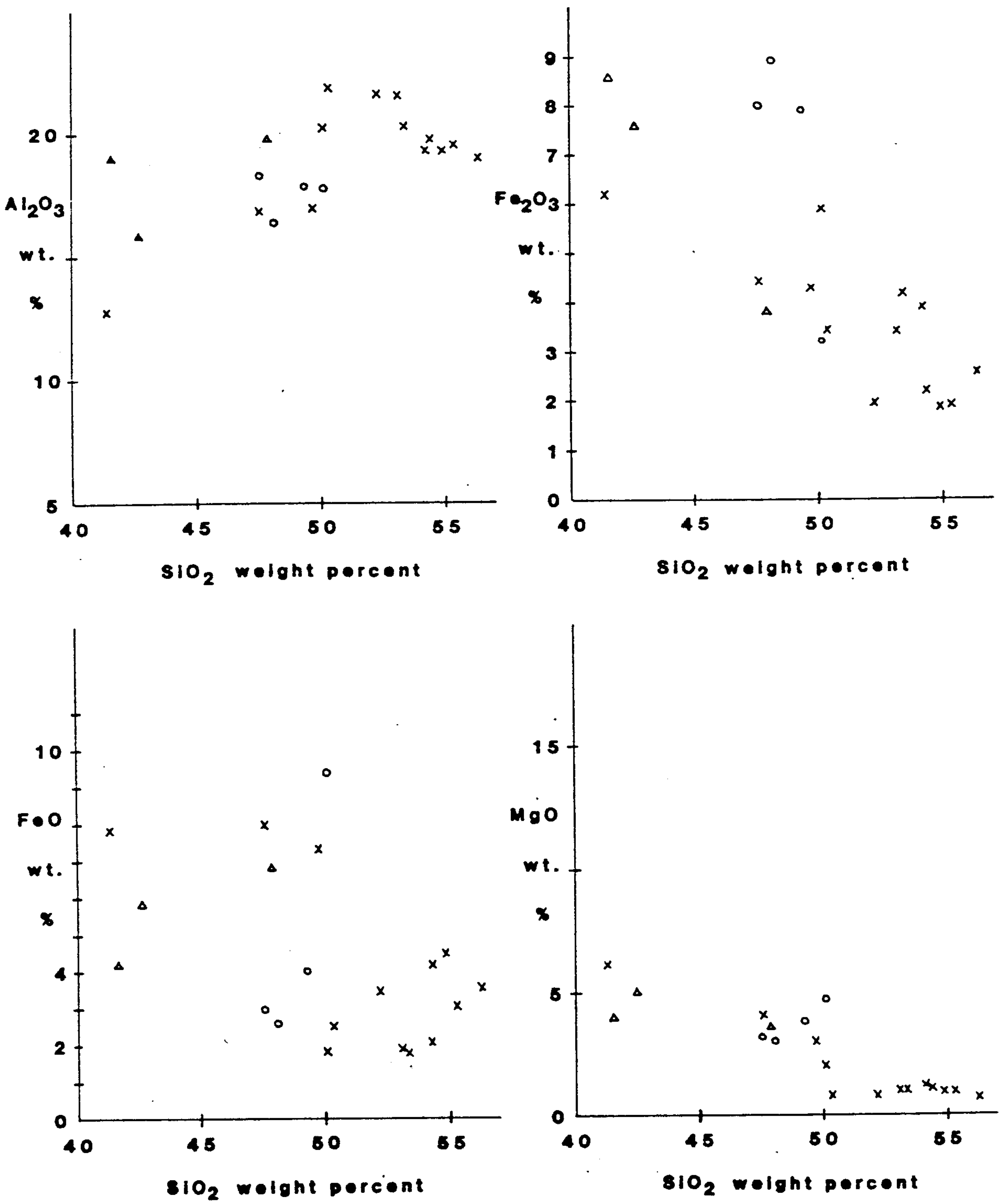
When plotted versus SiO_2, there are strong trends showing decreasing amounts of CaO, TiO_2, MgO, Fe_2O_3, P_2O_5, and H_2O and increasing amounts of Na_2O, Al_2O_3, and K_2O. At Kibo, the youngest volcanic center on the mountain, the opposite is true. Mawenzi contains intermediate concentrations of all the oxides (See Graphs 1, 2, 3, and 4).

The process of differentiation of a magma body is known as fractional crystallization. As a magma body cools, the first minerals to form are high in MgO, Fe_2O_3, and CaO, and low in SiO_2, K_2O, NaO, and Al_2O_3. Silica rich minerals are not able to form due to the shortage of SiO_2 in the melt. The minerals which form early are then removed from the magma body by settling to the bottom of the magma chamber. These minerals are no longer able to react with the melt and equilibrium crystalization ceases. The remaining magma becomes enriched in SiO_2, and depleted in MgO, FeO, and CaO. This change in magma composition directly affects the composition of the next minerals that form. Plagioclase becomes increasingly Na-rich as Ca is steadily removed from the melt. Olivine ceases to form and is replaced by pyroxene which in turn ceases to form in favor of hornblende (Ehlers and Blatt, 1982).

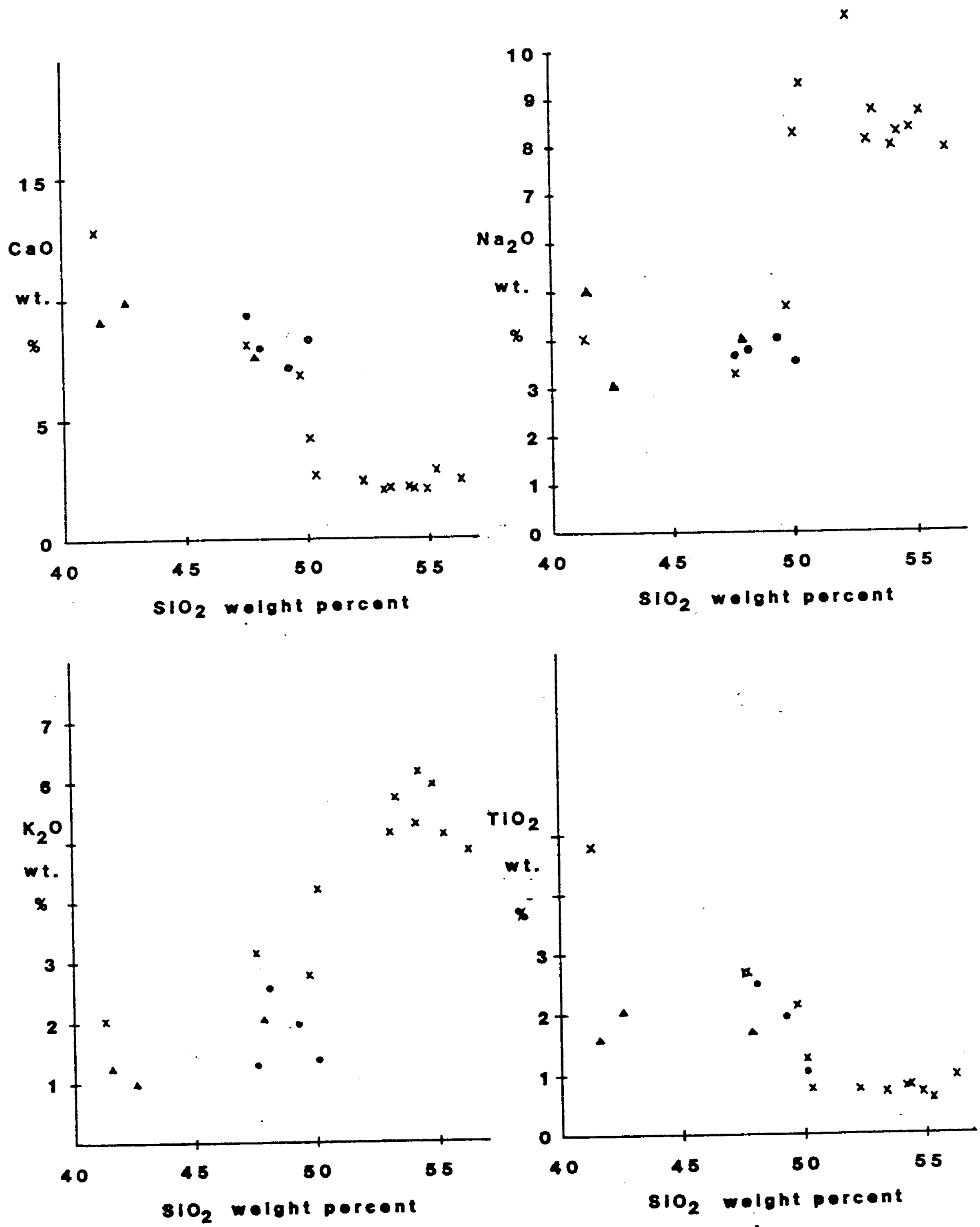
If this process is allowed to progress, the final product would be a granite magma. This has not happened on Kilimanjaro. Many differentiation trends are possible depending on such variables as original magma composition, the composition and amounts of precipitating phases, pressure,



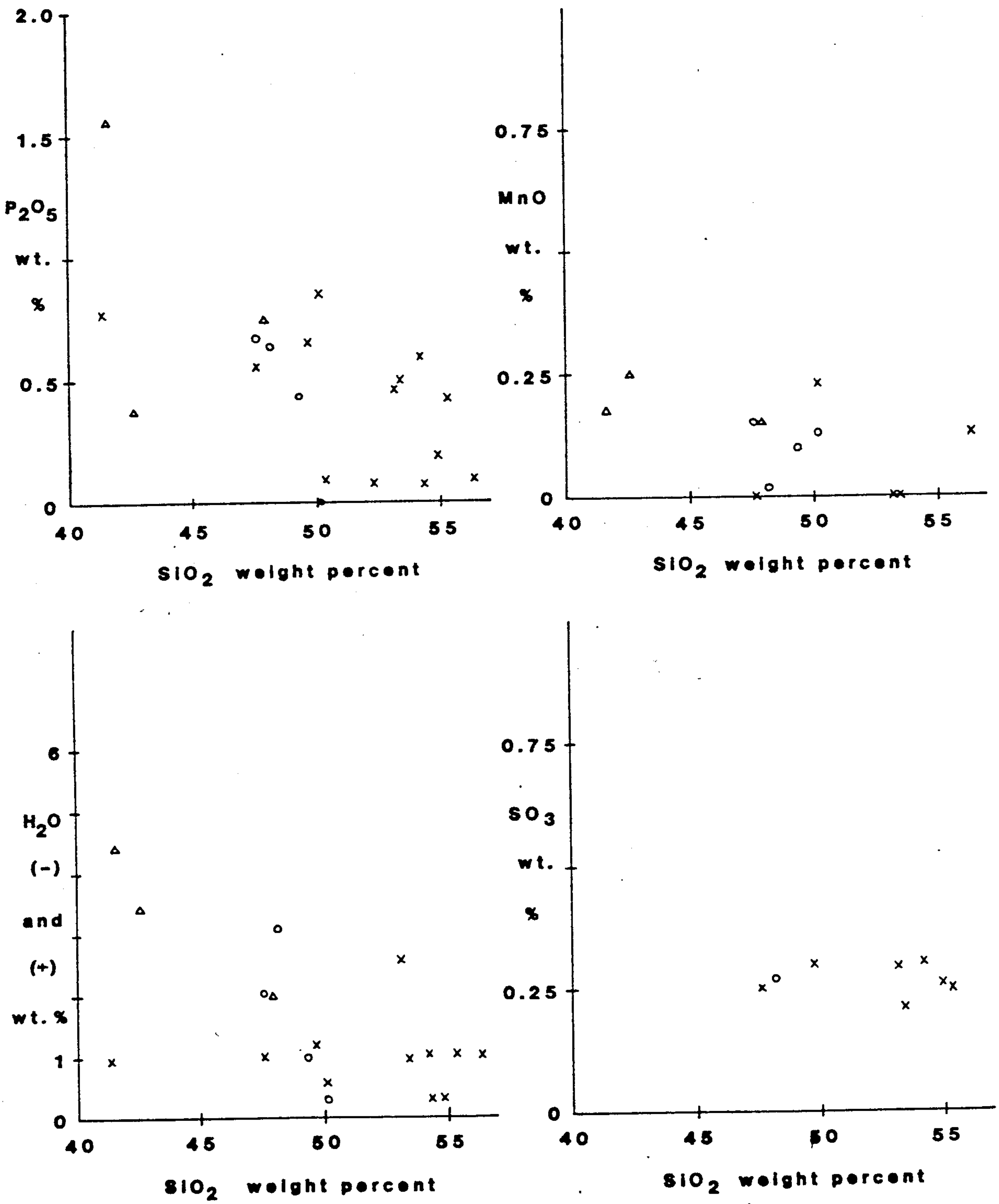
Graph 1. SrO, BaO, S, Cl, CO_2, and ZrO_2 versus SiO_2 Weight Percent (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).



Graph 2. FeO, MgO, Al_2O_3, and Fe_2O_3 versus SiO_2 Weight Percent (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).



Graph 3. CaO, Na_2O, K_2O, and TiO_2 versus SiO_2 Weight Percent (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).



Graph 4. P_2O_5, MnO, H_2O (-) & (+), and SO_3 versus SiO_2 Weight Percent (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).

	Shira			Mawenzi			
	A	B	C	D	E	F	G
SiO_2	42.58	47.93	41.57	48.11	47.54	49.35	50.15
Al_2O_3	15.84	19.86	19.16	16.41	18.32	17.91	17.82
Fe_2O_3	7.62	3.82	8.64	8.96	8.04	7.96	3.24
FeO	5.76	6.72	4.24	2.60	3.06	4.14	9.36
MgO	5.04	3.66	4.14	3.03	3.36	3.92	4.82
CaO	9.93	7.62	9.16	7.96	9.33	7.16	8.34
Na_2O	3.12	3.97	5.03	3.76	3.62	4.02	3.57
K_2O	0.99	2.04	1.22	2.55	1.28	1.96	1.38
TiO_2	2.04	1.68	1.56	2.50	2.66	1.96	1.03
P_2O_5	0.37	0.74	0.78	0.64	0.67	0.43	trace
MnO	0.25	0.16	0.18	0.02	0.15	0.10	0.13
H_2O+	2.12	1.40	3.28	3.10	0.98	0.94	0.06
H_2O-	1.30	0.59	1.06		1.09	0.05	0.24
SO_3	--	--	--	0.27	--	--	--
ZrO_2	--	--	--	0.27	--	--	--
CO_2	2.58	--	--	--	--	--	--
SrO	0.19	--	--	--	--	--	--
BaO	0.06	--	--	--	--	--	--
Total	99.79	100.19	100.02	100.18	100.10	99.90	100.14

Table 1. Chemical Analyses Of Specimens From Shira And Mawenzi (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).

Explanation of Table 1

A. Analcime-bearing olivine dolerite (K. 592), summit of Platzkegel, Shira,, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

B. Trachybasalt (K. 891), north end of Shira Ridge, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

C. Melanephelinite (K. 585), Shira caldera scarp, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

D. Basaltoider trachydolerit (essexit porphyrit), Mawenzi, Kilimanjaro. (Finckh, 1914, p. 453).

E. Glassy trachybasalt (K. 224), col at head of Sudtal, south Mawenzi, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

F. Olivine trachybasalt (K. 173), Sudtal 3, Mawenzi, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

G. Olivine trachybasalt (K. 189), west ridge of Sudtal, Mawenzi, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, p. 100).

Kibo

	H	I	J	K	L	M	N	O	P	Q	R	S	T
SiO_2	47.51	49.69	41.48	50.12	53.12	55.32	53.44	54.20	54.94	54.30	56.32	50.38	52.26
Al_2O_3	16.87	17.02	12.72	20.34	21.62	19.59	20.39	19.38	19.34	19.71	19.01	21.94	21.62
Fe_2O_3	4.41	4.28	6.24	5.96	3.46	1.92	4.22	3.83	1.80	2.23	2.66	3.47	1.99
FeO	7.99	7.34	7.72	1.88	1.94	3.12	1.76	2.14	4.52	4.21	3.59	2.59	3.55
MgO	4.27	3.15	6.29	2.14	1.10	1.11	1.12	1.35	1.11	1.19	0.78	0.94	0.96
CaO	8.07	6.73	12.86	4.23	2.00	2.72	2.13	2.15	2.05	2.08	2.48	2.63	2.40
Na_2O	3.26	4.67	4.04	8.28	8.16	8.73	8.76	8.01	8.39	8.29	7.95	9.28	10.74
K_2O	3.16	2.73	2.02	4.19	5.11	5.09	5.75	5.28	5.93	6.15	4.84	5.50	4.75
TiO_2	2.65	2.13	4.68	1.24	0.08	0.59	0.69	0.79	0.67	0.80	0.94	0.78	0.76
P_2O_5	0.55	0.65	0.77	0.84	0.46	0.42	0.49	0.58	0.18	0.15	0.19	0.19	0.15
MnO	trace	—	—	0.23	trace	—	trace	—	—	—	0.13	0.16	0.12
H_2O+	0.99	1.19	0.96	0.44	2.56	1.05	0.97	1.04	0.32	0.32	1.00	1.82	0.75
H_2O-			—	0.13		—		—	—		—	0.38	0.26
SO_3	0.25	0.30	—	—	0.28	0.26	0.22	0.31	0.27	—	—	—	—
ZrO_2	0.18	0.36	—	—	0.06	0.33	0.27	0.47	0.38	0.48	—	—	—
CO_2	—	—	0.32	—	—	—	—	—	—	—	—	—	trace
S	—	—	—	—	—	—	—	—	—	0.10	—	—	—
Cl	—	—	—	—	—	—	—	—	—	—	0.16	—	—
Total	100.16	100.24	100.10	100.02	99.95	100.25	100.21	99.53	99.90	100.01	100.05	100.06	100.31

Table 2. Chemical Analyses Of Specimens From Kibo (After Williams, L.A.J., 1969, Bulletin Volcanologique, 3).

Explanation of Table 2

H. Trachytoider trachydolerit, west Kibo, Kilimanjaro, Anal. Eyme. (Finckh, 1914, p. 453).

I. Essexit (basalt-trachydolerit), Kibo. Anal. Kluss. (Finckh, 1914, p. 453).

J. Augitite, limite d'ankaratrite, Kibo, Kilimanjaro. Anal. M. Raoult. (Lacroix, 1923, p. 263).

K. Glassy nepheline rhomb porphyry (K. 121), Summit Ridge, Kibo, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, pp. 99-100).

L. Nephelinrhombenporphyry, north-east Kibo, Kilimanjaro. Anal. Eyme. (Finckh, 1906, p. 373).

M. Rhombenporphyry, north Kibo, Kilimanjaro. Anal. Eyme. Quoted by Lacroix, 1923, pp. 261-2.

N. Leuzitrhombenporphyry, north-east Kibo, Kilimanjaro. Finckh 1906, p. 373.

O. Leucitrhombenporphyry, east Kibo, Kilimanjaro. Anal. Kluss. Quoted by Lacroix, 1923, pp. 261-2.

P. Katophorittrachyt, west Kibo, Kilimanjaro. Anal. Eyme. Quoted by Lacroix, 1923, pp. 261-2.

Q. Trachydoleritisches Glas, north-west Kibo, Kilimanjaro. Anal. Eyme. (Finckh, 1906, p. 373).

R. Obsidienne de Kenyte, south-west Kibo, Kilimanjaro. Anal. M. Raoult. (Lacroix, 1923, pp. 261-2).

Explanation of Table 2 (cont.)

S. Aegirine phonolite (K. 149) Ash pit, Kibo, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, pp. 99-100).

T. Aegirine phonolite (K. 128) Snout of Furtwangler Glacier, Kibo Caldera, Kilimanjaro. Anal. W. H. Herdsman. (Geol. Surv. Tanganyika, 1958, pp. 99-100).

and oxygen content of the magma (Ehlers and Blatt, 1982).

General Petrography

The ten thin sections described in this thesis show many similarities, yet at the same time display numerous differences. They contain the same major minerals, however, in vastly different sizes and relationships. Some are highly altered, while others are fresh. Vesicles are nearly absent in some, yet abundant in others. Overall, these samples attest to the wide variation in the lavas, if not actually the wide variety of lavas, found on Mt. Kilimanjaro and the surrounding area.

All ten samples have been classified as porphyritic aphanitic rocks. This indicates a period of partial crystalization in a magma chamber followed by ejection and completion of the crystallization process at the earth's surface. Phenocrysts make up one to 33 percent of the slides. Flow banding is visible in several of the thin sections. Flow banding refers to the orientation of microlites which takes place during the flow of molten material.

Plagioclase was found in all ten samples as subhedral laths ranging in composition from An_{27} to An_{60}. However, some of the composition determinations were made based on only 2 or 3 grains, due either to a lack of suitable orientation or nondistinct twinning. No composition was determined for three samples. Oscillatory zoning was found in some plagioclase phenocrysts. In those slides containing abundant plagioclase, the feldspar was generally free of alteration.

Clinopyroxene was found in nine of the samples as phenocrysts and/or matrix material. It was not found in association with orthopyroxene. Augite grains showing zoning were found in several slides and grains frequently were found with rims enriched in opaques. Occasionally these rims were also darker than the interior of the grains. Augite grains were occasionally altered to an amphibole.

Olivine was found in seven samples. It was frequently altered to iddingsite, in one sample it was altered to an opaque material, and in another slide free of olivine, serpentine was found.

Orthopyroxene was found in one sample. It was extensively altered to an amphibole.

Vesicles made up from one to 33 percent of the slides. They were frequently rimmed with small amounts of alteration material, but only rarely were they completely filled.

Opaques and apatite were common accessory minerals. Some of the opaques were oxidized to red hematite. When viewed under high power with the condensing lens in the opaques frequently had a purplish tinge.

Carbonate phenocrysts were found in one sample. A trace amount of alkali feldspar was found in the matrix of another.

Plagioclase and clinopyroxene commonly make up 80 percent of all basalts. In alkali basalts, olivine is present instead of orthopyroxene. Calcium-poor pyroxenes usually indicate a tholeiitic basalt (Morse, 1980). Magnetite and apatite are almost always present in basalts (Bates and Jackson, 1984).

According to Morse (1980), the combination of clinopyroxene, plagioclase, and olivine, coupled with the absence of orthopyroxene and nepheline classifies nine of the samples in this study as critically undersatuated Alkali basalts. The one exception combined the presence of orthopyroxene with the absence of quartz, olivine, and clinopyroxene, and has been termed a silica-saturated Hypersthene basalt.

Conclusion

Mt. Kilimanjaro has been classified a basalt-trachyte-phonolite volcano. Mt. Meru is characterized by nephelinites, tephrites, trachytes, and phonolites. Ngorongoro crater and Lake Manyara are comprised of the nephelinite-phonolite series (Williams, 1969).

The rocks in this study are critically under-saturated as is to be expected, but they do not contain the alkali feldspar and nepheline that is common to the area. Nevertheless they are not anomalous, as they fit readily the basalts that normally occur there.

Appendix

Thin Section Descriptions

Sample #588

Name: Alkali basalt

Collected from Ngorongoro Crater Lodge

Texture: Porphyritic aphanitic, flow banding visible

Minerals:

Plagioclase- 80% of slide as microliths in matrix, size- 0.14 x 0.02 mm, albite twinning; trace amounts as phenocrysts, size- up to 0.60 x 0.12 mm, albite twinning, An_{53}, lath-shaped subhedral grains.

Augite------ trace amounts as subhedral phenocrysts, also finely disseminated throughout matrix.

Opaques----- magnetite?, 20% of slide as matrix material, subhedral to euhedral squarish grains evenly distributed throughout slide, size- 0.02 x 0.02 mm, very few up to 0.40 x 0.20 mm, grains are often oxidized to red hematite.

Apatite----- trace amounts in matrix, size- 0.025 x 0.0125 mm.

Alteration-- Limonite is distributed throughout the matrix, but is also concentrated in several bands up to 2 mm wide; 40% of the slide is stained yellow.

Serpentine is present in trace amounts as a nonpleochroic, green, fibrous, alteration mineral, size- up to 0.70 x 0.26 mm , anhedral.

Hematite is common as an alteration of the opaques.

Green alteration of ferro-magnesium minerals is fairly common in the matrix.

Sample #589A

Name: Hyperstene basalt

Collected from Kilimanjaro

Texture: Porphyritic aphanitic

Minerals:

Plagioclase--- 30% of slide as microliths in matrix, size 0.025 x 0.009 to 0.12 x 0.02 mm, albite twinning, An_{60}, lath-shaped subhedral grains.

Orthopyroxene- hyperstene?, 15% of slide as colorless, anhedral to subhedral phenocrysts and matrix material, some grains are twinned; not all grains show parallel extinction, but do show two cleavage directions at almost right angles, and low birefringence; grains are both biaxial (-) and (+); some grains are zoned; grains are heavily altered, alteration products include an amphibole, and limonite staining; contain opaques.

Opaques------- 5% of slide; evenly distributed, subhedral, squarish grains; size- 0.01 x 0.01 to 0.10 x 0.07 mm.

Apatite------- trace

Alteration---- Amphibole, 2% of slide, pleochroic going from dark yellow to light yellow and clear, replaces the orthopyroxene.

Limonitic staining covers thirty percent of the slide, staining the orthopyrox ene,and matrix. The rock is highly altered. Many orthopyroxene grains have

Vesicles------ 10% of slide, often contain limonite; the length of the slide is crossed by a crack up to 0.70 mm wide containing small deposits of a fine-grained dark green material.

Remaining 38% of rock is made up of glass and material too fine-grained to identify with any accuracy.

Sample #589B

Name: Alkali basalt

Collected from Kilimanjaro

Texture: Porphyritic aph~~o~~anitic

Minerals:

Amphibole- 2% of slide, pleochroic going from reddish orange to yellow and yellowish orange to light green; anhedral to subhedral grains ranging in size from 0.20 x 0.12 to 1.30 x 0.65 mm; some grains contain opaques; some grains have partially dissolved leaving a void while others are fresh.

Augite---- 10% of slide, size- 0.01 x 0.01 to 1.30 x 2.20 mm; grains are light green in color, some are slightly pleochroic going from dark green to light green; some contain opaques and some are zoned; subhedral to euhedral.

Olivine--- 2% of slide, subhedral to euhedral grains ranging in size from 0.20 x 0.07 to 0.45 x 0.20 mm; colorless, some highly altered to an opaque material which forms lines of beads crisscrossing the olivine.

Opaques--- 3% of slide?, percentage is difficult to judge due to the dark color of the matrix; anhedral to subhedral grains range in size from 0.01 x 0.01 to 0.55 x 0.25 mm.

Matrix----- 50% of slide, glassy, color ranges from dark brown to dark red to yellow to light green; contains trace amounts of small plagioclase laths.

Alteration- 40% of the slide has been stained yellow with limonite. The stain is in two broad bands up to 7 mm. These two bands are separated by a brown band up to 12 mm wide.

Vesicles--- 33% of the slide, many are rimmed with limonite or fine-grained green material; size- 0.04 x 0.04 to 2.60 x 1.60 mm; shape is highly variable.

Sample #590

Name: Alkali basalt

Collected from Mt. Meru

Texture: Porphyritic aph~~e~~anitic

Minerals:

Augite------ 15% of slide, green subhedral grains, many are lath shaped, some are strongly zoned; size- 0.03 x 0.01 to 1.12 x 0.30 mm; some grains contain opaques and apatite, altered edges on many grains.

Plagioclase- 10% of slide, lath-shaped subhedral grains showing poorly developed albite twinning, twins grade into extinction; many grains have altered edges, some show oscillatory zoning; An_{27}.

Opaques----- 3% of slide, evenly distributed throughout slide, subhedral squarish grains ranging in size from 0.01 x 0.01 to 0.15 x 0.15 mm.

Apatite----- trace.

Matrix------ 52% of slide, dark greenish brown, glassy.

Vesicles---- 20% of slide, round to oval shaped; most are free of any deposits, some contain fragments of matrix material; size- 0.05 x 0.04 to 7.0 x 3.5 mm.

Sample #591

Name: Alkali basalt, trachybasalt?

Collected from Kibo and Mawenzi

Texture: Porphoritic aphenitic

Minerals:

Plagioclase- 24% of slide as phenocrysts, subhedral lath-shaped grains up to 11.25 x 2.5 mm; albite twinning, many show oscillatory zoning, An_{56}; 20% of slide as microliths in the matrix showing albite twinning, size 0.10 x 0.03 mm.

Olivine----- 12% of slide, anhedral to subhedral rounded grains; very light grey green in color, probably forsteritic; contains opaques, crossed by cracks filled with reddish brown material, some alteration to iddingsite.

Opaques----- trace as phenocrysts, anhedral to subhedral, size- up to 0.80 x 0.45 mm; 6% as matrix material, subhedral, size- 0.01 x 0.01 mm.

Amphibole--- 5% as matrix material, pleochroic going from green to brown and from green to clear, subhedral, size- 0.08 x 0.04 mm,

Vesicles---- 13% of slide, round.

Clinopyroxene-20% of matrix, lath shaped, greyish green

Apatite------ trace

Alkali feldspar-trace in matrix

Sample #592

Name: Alkali basalt

Collected from Kibo and Mawenzi

Texture: porphyritic aphanitic

Minerals:

Olivine---- 15% of slide, anhedral to euhedral, size- 0.06 x 0.05 to 1.15 x 0.90 mm, grains show little alteration, contain opaques, rim of some grains show a concentration of opaques, a few grains have a rim of fine-grained green alteration material up to 0.07 mm wide.

Augite----- 10% of slide, light green, slightly pleochroic going from light green to light brown, most are lath shaped, contains few opaques, size- 0.05 x 0.03 to 0.35 x 0.20 mm, some grains show zoning.

Opaques---- magnesite?, trace, size 0.01 x 0.01 to 0.17 x 0.12 mm, anhedral to euhedral.

Vesicles--- 7% of slide, size- 0.04 x 0.02 to 1.90 x 1.00 mm, shape is highly variable, some are partially filled with fine-grained light green to clear material, some completely filled with fine-grained hematite?

Matrix----- 68% of slide, very dark brown, glassy, contains trace amounts of feldspar, Limonite staining covers <2% of slide.

Sample #593A

Name: Alkali basalt

Collected from Kilimanjaro

Texture: Porphyritic aphanitic, flow banding visible, microlites are seen to go around large pyroxene grains.

Minerals:

Plagioclase- 70% of slide as matrix material, subhedral lath shaped grains range in size from 0.10 x 0.25 to 0.70 x 0.10 mm, An_{52}, albite twinning.

Augite------ 5% of slide as phenocrysts, light brownish yellow in color, anhedral to euhedral, contains opaques and vesicles, zoning is visible in some grains, size- 0.32 x 0.20 to 2.20 x 1.85 mm, some grains exhibit a concentration of opaques in rim, some grains contain a red mineral- hematite?, augite also makes up 10% of the matrix.

Olivine--------- 2% of slide as phenocrysts, colorless, subhedral grains ranging in size from 0.12 x 0.10 to 0.97 x 0.85 mm; also makes up 2% of matrix.

Opaques--------- magnetite? 10% of matrix, anhedral to subhedral squarish grains, size- 0.01 x 0.01 to 0.28 x 0.25 mm.

Apatite--------- trace.

Vesicles-------- <2%, size- 0.03 x 0.02 to 0.85 x 0.67 mm,

Staining-------- 20% of slide is stained with red hematite, yellow limonite, and an unidentified brown stain; staining is concentrated in a band up to 6.0 mm wide, but is spread unevenly throughout the slide.

Sample #593B

Name: Alkali basalt

Collected from Kilimanjaro

Texture: Porphyritic aphanitic, flow banding is visible

Minerals:

Plagioclase- 53% of slide as matrix material, subhedral laths, albite twinning is poorly developed, An_{52} determined using only three grains, size- 0.24 x 0.04 mm, microlites seen to go around phenocrysts of pyroxene and opaques.

Opaques----- magnetite? 12% of slide as matrix material, subhedral squarish grains ranging in size from 0.01 x 0.01 to 0.25 x 0.17 mm, evenly distributed throughout slide.

Augite------ 3% of slide as subhedral phenocrysts up to 1.35 x 1.15 mm, zoning is visible in some grains, rims show a concentration of opaques but little alteration, light brown in color; also makes up 20% of slide as matrix material, most grains in the matrix are lath shaped.

Olivine----- 2% of slide, colorless, size- 0.20 x 0.20 to 1.08 x 1.18 mm, contains opaques and some red material which could be hematite oxidizing the opaques.

Vesicles---- <2% of slide, size- up to 0.25 x 0.20 mm, clear of any alteration products.

Staining---- <2% of slide is stained yellow and brown.

Sample #594

Name: Alkali basalt

Collected from Lake Manyara

Texture: Porphoritic aphanitic

Minerals:

Plagioclase- 55% of slide as matrix material, subhedral laths, size- 0.14 x 0.02 mm, An_{40} determined using only two grains.

Augite------ 10% of slide, anhedral to subhedral light brown grains, size- 0.06 x 0.02 to 1.55 x 1.15 mm, some zoning present, rims are slightly darker than the interior of the grains, rims contain a concentration of opaques.

Olivine----- 5% of slide, colorless, anhedral to euhedral, size- 0.28 x 0.20 to 3.90 x 3.00 mm, grains contain opaques, many have a rim of iddingsite up to 0.05 mm, iddingsite has replaced up to 90% of some grains, some brown staining is also present in the grains.

Carbonate--- 2% of slide, anhedral phenocrysts up to 0.34 x 0.27 mm, also found in matrix.

Opaques----- 10% of slide, subhedral, size- 0.01 x0.01 to 0.07 x 0.07 mm, magnetite?.

Vesicles---- <2% of slide, size- 0.15 x 0.15 to 0.75 x 0.60 mm.

Matrix------ 20% of matrix is composed of very fine material that is probably tiny plagioclase and augite grains ,but this is uncertain.

Sample #595

Name: Alkali basalt

Collected from Horom~~ki~~bo

Texture: Porphyritic aphanitic

Minerals:

Augite----- 20% of slide, light green and light brown in color, anhedral to euhedral, rims are darker than the interior of grains and contain a concentration of opaques. The dark rims are up to 0.07 mm wide, size- 0.15 x 0.20 to 7.75 x 8.00 mm, large grains of augite contain anhedral amphibole, vesicles, opaques, anhedral olivine, small amounts of a pleochroic red material and matrix material; some grains are zoned, some grains have exsolution lamellae.

Olivine---- 10% of slide, colorless grains of anhedral to euhedral shape, size- 0.25 x 0.25 to 3.00 x 3.60 mm; crossed by prominent cracks; contains opaques and some brownish staining.

Amphibole-- 2% of slide, pleochroic dark yellow to clear, most grains surrounded by augite but some are found in the matrix, anhedral, size- 0.10 x 0.15 to 0.50 x 1.00 mm, some grains are heavily altered to a dark brown material.

Opaques---- 2% of slide, magnetite?, anhedral to subhedral, size- 0.01 x 0.01 to 1.85 x 1.15 mm.

Vesicles--- 3% of slide, variable shape, size- 0.10 x 0.10 to 0.75 x 1.25 mm, many are lined with fine-grained greyish material.

Matrix----- 53% of slide; dark brown, almost opaque, contains very fine-grained feldspar, opaques, anhedral clinopyroxene, and brown glassy material.

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